

The University of Chicago

SOME ELECTRICAL PHENOMENA  
IN ROTATING METALLIC  
CONDUCTORS

A DISSERTATION SUBMITTED TO THE FACULTY  
OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR  
OF PHILOSOPHY

DEPARTMENT OF CHEMISTRY  
DECEMBER, 1938

By  
SAM ISAAC WEISSMAN

CHICAGO, ILLINOIS

1945



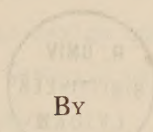


The University of Chicago

SOME ELECTRICAL PHENOMENA  
IN ROTATING METALLIC  
CONDUCTORS

A DISSERTATION SUBMITTED TO THE FACULTY  
OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR  
OF PHILOSOPHY

DEPARTMENT OF CHEMISTRY  
DECEMBER, 1938



By

SAM ISAAC WEISSMAN

CHICAGO, ILLINOIS

1945



#### ACKNOWLEDGMENT

I wish to express my gratitude to Dr. Simon Freed for encouragement and advice during the course of this work. Further I wish to thank Dr. Franklin Offner for indispensable aid in the design and construction of the electrical circuits which were used in these experiments.



Digitized by the Internet Archive  
in 2026

The existence of connections between dynamical and electromagnetic phenomena has been long suspected. Faraday (in whose writings one may find anticipation of an astonishing number of subsequent discoveries) searched for gravitational-electric-magnetic effects which seem to have been suggested to him by his previously discovered electromagnetic effects.<sup>1</sup> Helices connected by long wires to a stationary galvanometer were raised and lowered in the earth's gravitational field; various materials (iron, copper, bismuth) were placed within the helices. Special attention was paid to possible phenomena when the motion of the helix was suddenly arrested. All the results were null. Nevertheless, Faraday closed his description of these experiments with the statement, "Here end my trials for the present. The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity though they give no proof such a relation exists."

Related phenomena were considered by Maxwell.<sup>2</sup> Although Maxwell consciously avoided the inclusion of non-experimental mechanisms in his formulation of the laws of electromagnetism, he felt that experimental search for effects which might be associated with a hypothetical kinetic energy of electric current was worth while. Accordingly, Maxwell sought for a mechanical reaction on a conductor in which the current was rapidly changing and for gyroscopic properties of helices carrying steady currents. His

---

<sup>1</sup>"Faraday's Experimental Researches in Electricity," Bernard Quaritch, London, 1839, III, 161.

<sup>2</sup>"Maxwell's Treatise on Electricity and Magnetism," Clarendon Press, London, 1892, 3d ed., II, 211.



results were null.

Also null were the results of Hertz, who contrived to pass current along one diameter of a spinning disc and to seek for an electromotive force along the perpendicular diameter.<sup>1</sup>

These early experiments were of a purely exploratory nature; there was little basis for theoretical estimates of the magnitudes of the effects to be expected. But later progress in the study of positive ray, cathode discharge, X-ray, and spectroscopic phenomena led to detailed hypotheses as to the structure of electrification; it became possible to compute, on the basis of these hypotheses, magnitudes of the expected effects.

E. F. Nichols attempted in 1906 to measure an electromotive force between the center and periphery of a rotating disc of aluminum.<sup>2</sup> At this time the electron and proton had been recognized as fundamental particles, but it had not been decided which (if either) was the carrier of electric current in metallic conductors. Nichols' experiment was supposed to decide this point, but the experimental uncertainties were so great, principally because of the large and erratic electromotive forces produced at the brush contacts to the disc, that it was difficult to reach any conclusion. It did, however, seem improbable that a particle as massive as the proton could be the carrier of current in a conductor.

The experiments of R. C. Tolman and associates were more clear cut.<sup>3</sup> A rotating helix, connected by long twisted wires to

<sup>1</sup>Hertz, Wiedemann's Annalen der Physik und Chemie, 14, 581-90 (1881).

<sup>2</sup>Nichols, Physik Z., 7, 640 (1906).

<sup>3</sup>R. C. Tolman and Dale Stewart, Phys. Rev., 8, 97 (1916); 9, 164 (1917); Tolman, Heurer, and Guernsey, 21, 525 (1923); Tolman and Mott-Smith, 28, 794 (1926).



a ballistic galvanometer, was brought to a sudden stop; the galvanometer deflection measured the net flow of charge with respect to the conductor. The observed deflection agreed well with the quantity computed from a simple idealization: the metal was pictured as containing charged particles (with mass and charge of cathode particles), restrained by frictional forces.<sup>1</sup>

In later experiments a copper cylinder was oscillated about its axis; the alternating current was estimated from the current induced in a concentric stationary helix. This method was far more precise than the earlier one, but the results were in poorer agreement with those computed from the simple picture. Not only did the magnitude of the current disagree with the predicted one, but, perhaps more significantly, the phase difference between the current and motion differed by ten degrees from the expected phase difference.<sup>2</sup>

A series of gyromagnetic experiments, closely related to Maxwell's exploratory experiments, have been successfully performed

<sup>1</sup>The frictional forces were adjusted to match the known resistivity of the metal. At first sight it would seem that the density of conducting particles in the metal is an important barometer, but this quantity is absorbed with the "frictional force" on each particle into the single resistivity.

<sup>2</sup>This might lead one to suspect that the notion of a pure "frictional force" is too simple. Certainly the question of modification of Ohm's law for a conductor accelerated with respect to an inertial frame should be considered. If Ohm's law holds with respect to a frame fixed in the conductor, the frictional force on the charge is equilibrated by an electric field and there is no effect; this certainly is not the case. Of course, a modification of Ohm's law for non-isothermal metallic conductors has been accepted; the relation is written  $\underline{I} = K \nabla T + \underline{C} \underline{E}$ .  $\underline{I}$  is the current,  $K$  a Thomson coefficient,  $T$  the temperature,  $\underline{C}$  the electrical conductivity, and  $\underline{E}$  the electric field. For the case of a conductor accelerated with respect to an inertial frame, a third term, some function of the acceleration, would have to be included.

In addition there are perplexing problems concerning the connections between the properties of the conducting system as estimated by an observer fixed with respect to the conductor and an observer in an inertial frame.

during the last several decades.<sup>1</sup> It has been observed that when a body of magnetic material is rotated it becomes magnetized, and, conversely, when a magnetic body is magnetized it acquires angular momentum.

The experiments which will be described here are closely related to Nichols' experiment. Nichols, it will be recalled, attempted to estimate the electromotive force in a rotating disc from the current which passed through a galvanometer whose terminals were connected by brushes to the center and periphery of the disc. Nichols supposed that the carriers of current had both charge and mass, and that the work done on the current by the dynamical forces of the accelerational field would be equal to the work given to the external circuit by the current. Thus, if the mass of the carrier is  $m$ , the charge  $e$ , the radius of the disc  $r$ , its angular velocity  $w$ , and the apparent electromotive force  $M$ ,

$$Me = \frac{1}{2} mr^2 w^2 \text{ and,}$$

$$M = \frac{1}{2} m/e r^2 w^2 \quad (1.)$$

It has already been noted that sporadic phenomena, presumably originating in thermal effects at the brushes, masked whatever intrinsic effects there may have been.

Apparently a method of exploration which could avoid "material contact" with the moving system would circumvent some of the difficulties which Nichols met. Such a method is available in the phenomena of electrostatic induction; effects induced in stationary conductors near the moving system reveals some of the phenomena in the system.

The actual method used in this work is an adaptation of the scheme devised by Zisman<sup>2</sup> for the measurement of contact

---

<sup>1</sup>S. J. Barnett, Science, 30, 413 (1919); A. Einstein and W. J. De Haas, Verh. D. Phy. Ges., 17, 152 (1915).

<sup>2</sup>Zisman, R. S. I., 3, 7 (1932).

potential differences. The capacity between the two surfaces under investigation is varied periodically. The potential difference which must be applied between them so that no alternating current flows in the circuit is the contact potential difference between the surfaces. Let us investigate the behavior of such a system. Consider a conducting circuit terminating in a capacity between metals A and B. In the loop connecting the metal we have any combination of metallic conductors, sources of electromotive force, and a potentiometer.<sup>1</sup> Consider the potential changes on a path just outside the conducting region. The potential drop from a point just outside metal A to a point outside the conductor contiguous to it, say metal i, is  $V_{Ai}$  (where  $V_{Ai}$  is the contact potential difference between metal A and metal i), from a point outside metal i to a point outside the next metal  $V_{ij}$ , and so on. When a region where an electromotive force exists is encountered, the potential drop between points just outside the metals (say m and n) terminating the electromotive force is  $V_{mn} + \text{E.M.F.}_{mn}$ . Similarly for the metals at the terminals of the potentiometer, the contact potential difference is augmented by the potentiometer voltage. Continue around the circuit until a point just outside metal B is reached. The sum of the potential drops is  $V_{Ai} + V_{ij} + V_{mn} + \text{E.M.F.}_{mn} \dots V_{\text{pot.}} + V_{rs} \dots V_{tB}$  where t is the metal contiguous to B. According to the Volta law of tensions  $V_{Ai} + V_{ij} \dots + V_{mn} \dots + V_{tB} = V_{AB}$  where V is the characteristic contact

---

<sup>1</sup>We may define a source of electromotive force as an agency which maintains a difference in electrostatic potential between points just outside a pair of metals which differs from the characteristic contact potential difference of this pair. The contact potential difference is the potential difference between points just outside these metals when they are connected by metallic conductors, the whole system being isothermal, the time derivatives of the electric and magnetic fields vanishing, and the system at rest with respect to an inertial system.



potential difference between metals A and B.<sup>1</sup> The total potential drop along this path is then  $V_{AB} + \sum E.M.F. + V_{pot.}$ . We assume that there are no changing magnetic fields so that the electric field is conservative. The potential drop across the terminating capacity (from B to A) must then be  $-(V_{AB} + \sum E.M.F. + V_{pot.})$ . The magnitude of this potential drop is also given by  $Q/C$  where  $Q$  is the charge on the condenser and  $C$  its capacity.<sup>2</sup> Choose the sign of  $Q$  ( $C$  being always positive) so that  $Q/C = V_{AB} + \sum E.M.F. + V_{pot.}$ . Let us suppose  $C$  is a function of time;  $Q$  will also be a function of time and currents will flow in the system. If  $R$  is the total resistance of the conducting circuit,  $RdQ/dt$  is the additional potential drop which appears over the static case (assuming that the contact potential differences and electromotive forces are independent of current). If the inductance of the circuit is small the electric field remains almost conservative and

$$R \frac{dQ}{dt} + \frac{Q}{C} = V_{AB} + \sum E.M.F. + V_{pot.} \equiv V$$

This is a linear first order differential equation and we may write its solution immediately.

$$Q = e^{-\int \frac{dt}{RC}} \left[ \frac{V}{R} \left( \int e^{\int \frac{dt}{RC}} dt \right) + \text{const.} \right]$$

If  $V = 0$ , that is  $V_{pot.} = -(V_{AB} + \sum E.M.F.)$

$$Q = \text{const.} e^{-\int \frac{dt}{RC}}$$

<sup>1</sup>This law lacks strong experimental verification.

<sup>2</sup>Perhaps we should pay some attention to the experimental meaning of charge and capacity. We define as the condition of zero charge the state in which the potential drop between the plates of the condenser is zero. The charge at potential  $V$  is determined by a ballistic measurement of the flow when the potential is brought from zero to  $V$ . The proposition from electrostatics is that there is a linear connection (capacity) between charge and potential difference. Thus the entire system may have a charge (as determined by the surface integral of the dielectric displacement vector over a closed surface including the system) while the condenser itself is uncharged, and vice versa.

$$e^{-\frac{7}{RC} \frac{dt}{dt}}$$

Since  $RC$  is always positive,  $e^{-\frac{7}{RC} \frac{dt}{dt}}$  becomes vanishingly small with increasing time and the steady state solution is  $Q=0$ . Hence when  $V_{POT.}$ , the potential between the terminals of the potentiometer, just balances the contact potential difference between the plates of the condenser plus the sum of the electromotive forces, no alternating current flows in the circuit.

We can also show that whenever the alternating current remains zero the applied potential must again be equal to the contact potential plus the sum of the electromotive forces. In this case  $Q = \text{const.}$ ,  $dQ/dt = 0$ , and  $Q/C = V$ . Since  $V$  is independent of time  $Q/C$  must be independent of time. Since  $C$  varies with time,  $Q$  must vanish. Hence if  $dQ/dt = 0$ ,  $Q = 0$ , and  $V = 0$ . Thus we have a means of measurement of electromotive force in a circuit which lacks a complete conducting loop; for the condition that no alternating current flows in the circuit when the capacity is changed periodically determines a relation between applied potential, electromotive force, and contact potential difference. The experimental application of this method will be discussed later.

Let us return now to a consideration of the rotating metallic conductor. If, in the circuit illustrated schematically in Figure 1, in which  $B$  is the rotating disc,  $A$  an electrode with

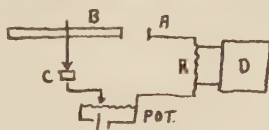


Fig. 1

capacity to the periphery of the disc,  $C$  a contact to the axis of rotation,  $R$  a resistance,  $D$  a detector of alternating current, we vary the capacity between  $A$  and the periphery and test for null alternating current, we measure the electromotive force in the disc plus the contact potential between  $A$  and  $B$ . It is difficult

to anticipate the effect of rotation on the contact potential. To me it seems that a similar statement might be made concerning the electromotive force in the disc, but widely accepted idealizations concerning conduction in metals lead to this type of picture:<sup>1</sup>

In the steady state an electron at radius  $r$  has an acceleration inward  $\omega^2 r$ . By Newton's second law there must be a force on the electron. This force can be supplied by an electric field so that at radius  $r$  there must be an electric field directed along the radius to make  $eE = m r \omega^2$ .

Hence  $E = (m/e) r \omega^2$  and  $\int_0^R E \cdot dr = \frac{1}{2} \frac{m}{e} R^2 \omega^2$ . According to this picture the electromotive force would depend only on the size and angular velocity of the disc (provided electrons in all metals are the same). It is not easy to believe that antimony and copper and bismuth and aluminum and iron would behave in the same way. If the electron swarm in the metal is allowed to have the properties of a gas, pressure gradients in the gas could help maintain equilibrium. The "density" of the electron gas (which might be considered a parameter which varies from metal to metal) would determine how much of the equilibrating force is electric field and how much pressure gradient.<sup>2</sup>

<sup>1</sup>For a system of this type it may not be possible to disentangle the concepts of contact potential difference and electromotive force.

<sup>2</sup>Effects of convection currents arising from the motion of the charged conductor may be important. If we suppose that a radial electric field proportional to the radius exists in the rotating disc there is a body charge density in the disc. In cylindrical coordinates  $E_z = 0$ ,  $E_\theta = 0$ ,  $E_r = kr$

$$\nabla \cdot E = \frac{1}{r} \left[ \frac{\partial}{\partial z} (r E_z) + \frac{\partial}{\partial \theta} (E_\theta) + \frac{\partial}{\partial r} (r E_r) \right] = 2k$$

If  $\epsilon$  is the dielectric constant,  $\rho = \nabla \cdot (\epsilon E) = 2\epsilon k$

(The concept of dielectric constant of a conductor is a hazy one.) There will also be surface charges depending on the geometry of the system and its total charge. The motion of such a charged system would presumably give rise to magnetic fields which might in turn modify the electric fields. The problem is difficult because of the uncertainties over a proper set of transformation



Perhaps some of the quantum mechanical treatments of phenomena in metals (such as Sommerfeld's application of Fermi statistics) might be fruitful methods of approach; I am not familiar enough with them to say. My own feeling is that it will be no more possible to arrive at a satisfactory formulation of the kind of phenomena which we have been discussing from the results of observation on stationary systems than it was to infer the laws of electrodynamics from the laws of electrostatics.

---

equations between a frame fixed in the moving system and an inertial frame.

## EXPERIMENTAL SECTION

It was proposed to measure the electromotive force in a rotating conductor by the method whose principles have already been given. The rotating system was of the vacuum type devised by Beams and associates.<sup>1</sup> The essential portions of the rotating mechanism and electrode assembly are indicated in Figure 2.

The brass stator had twelve jets, drilled with a #74 drill so that the orifices of the jets formed a circle of 1.25 cm. diameter. The jets were oriented so that they pointed upward at an angle of  $30^{\circ}$  with the horizontal, and so that the projection of each jet into the plane of the orifices made an angle of  $8^{\circ}$  with the tangent to the circle containing the orifices at the exit of each jet. The turbines are sufficiently described by the drawing. The dimensions of the rotors used in many of the experiments are given in the drawing. Special characteristics of each rotor will be given in the descriptions of the experiments involving each of the rotors.

Around the stator were wrapped two layers of sponge rubber (obtainable at Woolworth's under the title "Stick On Weather Strip") against which were pressed three supports of the type indicated in Figure 4. The amount of compression in the rubber could be regulated by the three radial screws indicated in Figure 4. This compression is important because it affects the frequency and amplitude of some of the vibrations which are encountered as the rotor is accelerated. The ring through which the screws passed was attached to a set of ways (made from a jeweler's

---

<sup>1</sup>Beams, R. S. I., 26, 299 (1935).

slide rest and a discarded milling attachment from the machine shop) so that adjustment of the position of the stator was possible. The entire assembly was suspended over the chamber from an I beam.

The bearing was of the conventional type described by Beams. Molecular Lubricant C--an oil said by the manufacturer to have a vapor pressure of  $10^{-7}$  mm.--was used as lubricant. For some of the earlier experiments the oil was forced into the bearing by a simple piston arrangement. In the later experiments the oil was first pumped on (to remove dissolved air) with a two stage mercury pump, and then forced into the bearing. These operations were performed with the apparatus illustrated in Figure 3.

The vacuum chamber was made of rolled brass; permanent brass to brass joints were soft soldered. A groove was machined in the cover of the chamber to fit a ridge in the flange at the opening of the chamber. The join was made vacuum tight with Apiezon Wax W.

The chamber was enclosed in a steel cylinder to which were bolted, top and bottom, chrome-vanadium steel discs. This steel container (weighing about 80 lbs.) was supported on wooden blocks which were bolted to a steel plate 22" X 16" X 3/4". The steel plate rested (by three leveling screws) on three discs of steel which, in turn, rested on felt pads on a laboratory desk.

For reasons which will be explained later it was necessary to make electrical contact to a point on the axis of the rotor. This contact was made between a pool of gallium or gallium-indium alloy and a sharp brass spike at the bottom of the rotor. The pool was mounted on a screw which could be manipulated from outside the vacuum chamber. The screw (size 7/16-40) fitted into a nut which was threaded over a full inch and a half. A heavy



grease--a mixture of Apiezon W and Molecular Lubricant C--packed into the threads made an effective vacuum seal.

The construction of the pool is indicated in Figure 2. For some of the earlier experiments pure gallium was used in the pool. The freezing point of this material is about  $30^{\circ}\text{C.}$ , but it is very easily supercooled. The gallium-indium alloy (the eutectic mixture of 80% gallium and 20% indium) freezes at  $16^{\circ}\text{C.}$  Mercury was not suitable for the contact because of its comparatively high vapor pressure. The vapor pressure of gallium is probably very low since its boiling point is about  $2,000^{\circ}\text{C.}$

The construction of the vibrating electrode presented certain difficulties, not all of which have as yet been satisfactorily surmounted. For maximum sensitivity the electrode and lead should have high impedance to ground. This requirement necessitates the use of a rather large piece of insulating material as the support for the electrode. But, since it seems to be almost impossible to maintain insulating material uncharged, the motion of the electrode system in itself produces large alternating electric fields unless the insulator is well shielded. Indeed, the input into the amplifier from this source may completely mask the desired voltage. Accordingly, the assembly shown in Figure 9 was used. The shaft carrying the electrode passed into the vacuum chamber through an oil gland similar to the one used for the rotational bearing. This shaft was driven by a piezo electric loud speaker motor (R-#25, Brush). The piezo electric unit was mounted on a steel slide (similar to a lathe slide) so that the distance between electrode and rotor could be varied. The alternating current for the crystal was supplied by a mechanical generator and 8 watt public address amplifier.

A one mil nickel wire was fastened by means of a small

screw to the back of the electrode. The wire led to a copper wire which passed through an insulator in the side of the chamber and thence to the amplifier. This insulator was a piece of clear bakelite one inch in diameter; it was screwed into the side of the chamber and sealed with Apiezon W. The resistance of the insulator under operating conditions was at least 500 megohms. The lead from the gallium pool was brought out through a similar insulator.

The details of the electrical circuit are given in Figure 5. The resistance  $R$ , and condenser  $C$ , were contained in a copper box between the amplifier and chamber. It is necessary to couple into the amplifier through a capacitor rather than a conductor because of the existence of grid current in the input stage. Associated with this current is a potential drop in the resistor  $R$  which must not appear in the measuring circuit. Indeed, during a particularly humid spell, the potential readings became very erratic and the trouble finally was traced to an electrical leak in the condenser  $C$ . Replacement of the old condenser (an ordinary 1000 volt mica condenser) by a Cornell-Dubilier type 2 condenser to which was added a grounded guard ring (a girdle of graphite around the condenser) remedied the difficulty.

Let us turn now to some of the experimental observations. Originally, I had hoped that it might be possible to use a capacitative coupling to the center of the rotating disc. Such a procedure would have left the rotor electrically insulated ("floating") from the rest of the system. An analysis similar to the one already given indicates that if the total charge on the insulated system is kept constant, the appearance of an electromotive force in the system may be determined from a change in the potentiometer reading at zero alternating current. A few experiments

soon revealed that the condition of constant charge was unattainable. For instance, in one experiment, the potential with respect to ground of a piece of copper mounted on several inches of paraffin changed at the rate of one volt per ten minutes. Similar phenomena appeared consistently; one inch steel shielding and vacuum of better than  $10^{-5}$  mm. made little difference.<sup>1</sup>

The first experiments with the spinning rotor also revealed some unanticipated phenomena. The rotor for these experiments was made of 17 ST duralumin.<sup>2</sup> The shaft was of piano wire .034" diameter; the chuck and set screws, the contact spike, and the driving turbine were all made of steel. The rotor was freshly machined with a carbon steel tool which had been previously "cleaned" by use in machining another piece of the duralumin stock from which the rotor had been made. As the rotor was spun, a wave whose frequency was the same as the frequency of rotation<sup>3</sup> and whose magnitude corresponded to a voltage swing on the grid of the first tube of about seventy microvolts root mean square appeared in the output of the amplifier. The magnitude of this wave was so great that it was impossible to make any measurements with the vibrating electrode.

Since it seemed necessary to eliminate this wave, considerable time was spent in a search for its cause or causes. The first surmise was that the wave corresponded to a variation in the contact potential around the periphery of the rotor. Were this the case, the magnitude of the input should have increased greatly when the contact at the gallium pool was made, for the circuit

---

<sup>1</sup>Cosmic rays have been suggested as the cause.

<sup>2</sup>Nominal composition: Cu 4.0%, Mn .5%, Mg .5%, Al 95.0%.

<sup>3</sup>The pitch of the sound in headphones across the output and of the sound of the turbine were identical.

loop would have included the rotor and its impedance to ground. As a matter of fact there was a noticeable decrease (about 30 per cent) in the magnitude of the wave when the contact was made. Furthermore, the contact potential at points around the periphery of the rotor were measured by the vibrating electrode with the results shown in Figure 6a. The type of wave recorded on the oscilloscope when the rotor was spun immediately thereafter is shown in Figure 6b. There is no apparent correspondence.

It will be noted that in a complete wave length there are three large peaks; the steel clutch in use for this experiment had a threefold symmetry (three set screws). The natural suspicion was, then, that perhaps the effect was a magnetic one. Whereupon, the chuck was replaced by one of beryllium copper, the turbine by one of phosphor bronze, and the spike by one of brass; the steel shaft was retained. Figure 7 depicts the type of wave produced after this change was made. Examination of the steel piano wires showed that they were strongly and non-uniformly magnetized. A .040" tungsten shaft was next tried. Observations were made on both directions of rotation; the waves are shown in Figure 8. It will be noted that in a rough way curve II may be obtained from curve I by the transformation  $t = -t'$ . This would indicate that the effect is a purely electrical one, for, if the effect were magnetic, reversal of direction of rotation would not only reverse the order of events ( $t = -t'$ ) but reverse the signs of the induced voltages ( $y = -y'$ ). This conclusion was further verified by the fact that a thin grounded metallic shield placed between the rotor and electrode completely removed the wave.

Another question of interest arose: does the potential of the rotor as a whole vary periodically, or does the rotor carry an inhomogeneous electric field around with it as it rotates? The



second alternative is supported by the observation previously noted concerning the effect of "grounding" the rotor. It is further supported by the observation that a cylindrical electrode which surrounded the rotor completely, yielded a much smaller voltage than the ordinary type of electrode.

All these observations seem to point to the conclusion that in the neighborhood of the rotor there is the type of electric field which one would expect from charged dielectrics. The large amplitudes of motion which are encountered in this experiment allow a small charge to give rise to a very considerable alternating field.

But, whatever the explanation of these waves, it was necessary to remove them before any progress toward the originally planned experiment could be made. The rotor material was changed to duralumin 14 ST<sup>1</sup> and the shaft to beryllium copper.<sup>2</sup> The high vacuum system, which contained a three stage mercury vapor pump and two traps, one of which was kept at solid carbon dioxide temperature and the other at liquid nitrogen temperature, was put into operation. The chamber was maintained at a pressure of about  $2 \times 10^{-5}$  mm. for five hours. A wave of the type indicated in Figure 10 was observed when the rotor was spun; the pressure was maintained low during this operation. While the rotor was spinning the periphery was touched with a sharp edge of 14 ST duralumin. This manœuvre had been intended to remove material responsible for the offending wave from the rotor. Like many of the other procedures which were tried during this investigation it intensified the trouble which it was supposed to cure. A complex

---

<sup>1</sup>Nominal composition: Cu 4.4%, Si .8%, Mn .75%, Mg .35%.

<sup>2</sup>This material is much more resistant toward fatigue than tungsten. It is diamagnetic.

wave of higher magnitude than the original resulted. Subsequent examination of the rotor showed that what had initially been a smooth shiny surface had become rather badly scored.

In a later experiment the pumping was carried out for fifty hours. Again the troublesome wave appeared (see Figure 11a.) Scraping with a rounded scraper made of .001" aluminum foil yielded the result shown in Figure 11b. Other attempts along the same lines were as ineffective as those described. In all the later experiments the wave persisted. Furthermore, there was a singular similarity between the waves obtained at different times under widely differing conditions. The rotors were changed; the pressure in some experiments was so low that it could not be read on a McLeod gauge, while in others it was as high as 1mm. There was available for a short time a General Radio Wave Analyzer.<sup>1</sup> Three different runs, the rotor having been machined between runs I and II, gave the following results for the harmonic analysis of the wave:

|                 | I    | II   | III  |
|-----------------|------|------|------|
| Fundamental     | 1.00 | 1.00 | 1.00 |
| Second harmonic | 1.25 | 3.40 | 3.31 |
| Third harmonic  | .32  | 1.04 | .61  |
| Fourth harmonic | .32  |      | .68  |

In every case the second harmonic is the strongest component.

Since it seemed impossible to avoid the production of the undesired wave in the input circuit, suppression of this wave in the amplifier suggested itself as an expedient which might allow the accomplishment of the originally contemplated measurement. With this end in mind the feedback network illustrated in the

---

<sup>1</sup>We are indebted to Mr. Johnston of the Stewart-Warner Corporation for the loan of this beautiful instrument.

circuit diagram was adopted.<sup>1</sup> Selectivity data of the amplifier are given in the following table:

| Frequency      | Relative Amplification |
|----------------|------------------------|
| 200 . . . . .  | .003                   |
| 225 . . . . .  | .010                   |
| 275 . . . . .  | .027                   |
| 290 . . . . .  | 1.000                  |
| 325 . . . . .  | .017                   |
| 400 . . . . .  | .009                   |
| 600 . . . . .  | .003                   |
| 1000 . . . . . | .0015                  |

The L-C circuit in the grid circuit of the fourth stage suppresses the very high and very low frequencies sufficiently so that the feedback circuit may operate stably.

A few trials indicated that the use of this sharply tuned amplifier would make possible measurements with the vibrating electrode. The frequency of vibration of the electrode was set at 290 cycles per second; the amplifier was, of course, tuned to this frequency. The minimum frequency of rotation at which measurements were possible was about 375 revolutions per second; below this speed too much of the unwanted wave was passed by the amplifier. Either an oscilloscope or microammeter with rectifier could be used for detection of the minimum amplifier output. When the oscilloscope was used, the minimum was most readily discerned when the linear sweep circuit was synchronized with the remnant of the rotational wave and the potentiometer set so that this wave was least blurred by the vibration of the electrode.

At this point it might be well to outline fully the procedures which were used in preparation for a measurement. The first task was a complete scraping with emery paper of the inside of the chamber; this operation was supposed to remove insulating films from the walls. Next, the pool contact was filled with

---

<sup>1</sup>H. H. Scott, Proc. I. R. E., 26, 226 (1938).

gallium indium alloy. The electrode was then prepared as follows: the electrode, wire, insulator, shield, and shaft were assembled. This assembly was grasped in a vise made of the same material as the electrode. The electrode, held in this vise, was given its final machining with a "clean" milling cutter of 10 cm. diameter. The position of the electrode on the milling machine was adjusted so that the shaft was along a radius of the cylindrical electrode surface. The electrode was removed from its vise, the shaft slipped through its bearing in the chamber, and soldered to the crystal driving unit. This method allowed one degree of freedom in the alignment of the electrode, and, to my regret, no better method than free-hand setting was developed for this part of the procedure. The nickel wire was then soldered to the input lead.

The rotor, with shaft attached, was grasped in a four jawed chuck, carefully centered in the lathe to within .0003" as determined by a dial gauge, and machined over the portion of the surface S (Figure 2). The rotor was removed from the chuck, carried to the laboratory in a special container (made from a coffee can), and placed in the chamber; the operation was considered unsuccessful if the surface was touched at any time after machining. Next, the cover was sealed on the chamber and the oil guard disk and bearing slipped into place. After the stator was centered on the bearing, the shaft was soldered to the friction clutch of the turbine, and the stator raised to the highest point which would allow the rotor to hang freely. At this point, application of air pressure in the stator and oil pressure in the bearing would (the gods willing) bring the rotor up to speed.

During the acceleration of the rotor the contact pool was withdrawn. Contact was made after the rotor had passed its vibration periods. This operation was performed as follows: the lead



from the potentiometer to the pool was disconnected from ground by the opening of a switch in the potentiometer. The pool was raised until a sudden disturbance appeared in the output of the amplifier. The appearance of this disturbance signified that the contact was established.

Many of the attempted experiments will not be recorded here since they served only to teach me the diagnosis of various ailments of the apparatus, such as burned out bearings, crooked shafts, clogged oil lines, leaking oil lines, etc.

In the first experiment, the rotor, of 14 ST, was spun for one hour at eight hundred revolution per second in a vacuum of  $5 \times 10^{-3}$  mm. At the end of the hour, measurements were made with the following results:

| Time in minutes | 0     | 3     | 5     | 7     | 9     | 11    | 15    | 17    | 21    | 25    |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Voltage         | .0243 | .0249 | .0250 | .0255 | .0260 | .0260 | .0266 | .0276 | .0283 | .0289 |

In the next experiment the procedure was repeated with essentially the same results. At the end of two hours, air was admitted to the chamber to a pressure of two centimeters. There was an immediate change in potential. The chamber was pumped out to  $5 \times 10^{-3}$  and again filled with air to two centimeter pressure. Again there was an immediate change in potential. The results are plotted in Figure 12.

These results indicated that the changes were connected with the gas pressure in the chamber. The next experiment yielded further information on this point. When the pressure was brought to  $10^{-5}$  mm., the rate of change of potential with time was substantially decreased. The results are shown in Figure 13.

That long pumping might remedy the situation was suggested by these experiments. The chamber was maintained at  $10^{-5}$  mm. for three hours while the rotor was stationary. The rotor was then

spun and the following measurements were obtained:

| Time in minutes | 0    | 5    | 11   | 15   | 20   | 32   | 40   |
|-----------------|------|------|------|------|------|------|------|
| Voltage         | .018 | .018 | .018 | .018 | .018 | .018 | .014 |

Unfortunately, the alignment of the electrode was such that the sensitivity was not high. A sudden violent vibration (probably connected with scoring of the bearing) set in after forty minutes of spinning; simultaneously there was a change in pressure and a change in voltage.

Essentially the same results were observed in the succeeding experiment. This time the pumping continued for five hours before the measurements were begun. Here are the potential measurements taken at a velocity of one thousand revolutions per second:

| Time in minutes | 0     | 20    | 25    | 30    | 35    | 40    | 46    | 51    | 56    |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Voltage         | .0089 | .0106 | .0109 | .0113 | .0115 | .0117 | .0117 | .0117 | .0116 |

The only additional information yielded by the next experiment was that a velocity change from four hundred to eight hundred revolutions per second made no change (within  $10^{-4}$  volts) in the potential. The change had been accomplished in ten minutes, during which there had been no pressure change. The effect of velocity change was further tested when the rotor was accelerated, brought to a complete stop, and reaccelerated. The results are shown in this table:

| Time in minutes    | 0     | 35    | 60    | 70    | 100  | 130   |
|--------------------|-------|-------|-------|-------|------|-------|
| Velocity in r.p.s. | 600   | 600   | 400   | 600   | 0    | 600   |
| Voltage            | .0390 | .0390 | .0395 | .0399 | .039 | .0392 |

The pressure fluctuated between  $8 \times 10^{-6}$  mm. and  $2 \times 10^{-5}$  mm. during

the course of the experiment. It is significant (and encouraging) that the change in contact potential difference during the spinning and stopping operations was no greater than the change which might have been anticipated from the normal rate of change under the vacuum conditions which had been obtained.

At this stage the vacuum system was rebuilt. The original three stage pump was used as a backing pump for a very fast conical nozzle type pump. The size of the glass tubing in the vacuum line was changed from 28 mm. to 32 mm. Simultaneously, the technique for machining and aligning the electrode was somewhat improved, so that the sensitivity of measurement was increased.<sup>1</sup> Unfortunately, there occurred after the improvement of the vacuum line a series of mishaps which did not allow a full test of the new arrangement. Among these was a deceptive and erratic leak in the system supplying oil to the gland of the vibrating electrode. Sudden increases and decreases in the pressure resulted from this leak. Electrical evidence of each pressure change was very long in disappearing.

Following is a series of contact potential differences between stationary rotor and vibrating electrode after eighteen hours of pumping under the aforementioned conditions:

| Time<br>in<br>hours | 0     | 1     | 1.5   | 2.25  | 4.5   | 5.8   | 7.8   | 8.0   | 9.5   | 9.9   |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Volt-<br>age        | .0100 | .0104 | .0110 | .0110 | .0114 | .0109 | .0113 | .0111 | .0105 | .0105 |

The measurements on the spinning rotor were unreliable because of a leak in the oil draining system. There was evidence of pressure changes during the above measurements.

---

<sup>1</sup>The sensitivity depends on the uniformity of the surfaces as well as on the geometry of the electrode.

The next data revealed little new except that measurements were made to ten microvolts and that another property besides contact potential was measured. It was mentioned earlier that a "floating" metallic conductor does not maintain a condition of constant charge. The rate of charge pickup of the rotor was estimated as follows: with connection to the rotor established, the potentiometer was set ten millivolts away from the null point; the connection was broken and the time required to reattain null alternating current noted. Data on this phenomenon and on the contact potential are given in the following table:

| Time in Hours<br>after Start-<br>ing Pumps | Pressure<br>in mm. | Time to Pick<br>Up Ten Milli-<br>volts, in<br>Seconds | Potenti-<br>ometer<br>Reading | Velocity |
|--------------------------------------------|--------------------|-------------------------------------------------------|-------------------------------|----------|
| 5                                          | $10^{-6}$          | 20                                                    | .0220                         | 0        |
| 7                                          | $10^{-6}$          | 24                                                    | .02169                        | 0        |
| 7.5                                        | $10^{-6}$          | 25                                                    | .02164                        | 0        |
| 8                                          | $10^{-5}$          | ..                                                    | .02153                        | 0        |
| 26.5                                       | $10^{-6}$          | ..                                                    | .0128                         | 0        |
| 27                                         | $10^{-5}$          | 26                                                    | .0117                         | 0        |
| 27.5                                       | $10^{-6}$          | ..                                                    | .0115                         | 0        |
| 32                                         | $10^{-5}$          | ..                                                    | .0181                         | 800      |
| 32.3                                       | $2 \times 10^{-5}$ | ..                                                    | .0166                         | 800      |
| 33.3                                       | $2 \times 10^{-5}$ | *200                                                  | .0095                         | 660      |
| 33.6                                       | $2 \times 10^{-5}$ | * 5                                                   | .0100                         | 1000     |
| 34                                         | $2 \times 10^{-6}$ | * 8                                                   | .0085                         | 1000     |

Asterisks before figures in the third column indicate that positive charge is gathered; lack of asterisks indicates that negative charge is picked up.

The reversal in sign of the charge gathering phenomenon under rotation is to be noted.

The final experiment was marred by a leak in the system carrying oil to the bearing. A slow leak was thereby introduced during the time the rotor was stationary, and a large quantity of air was forced into the vacuum chamber at the beginning of the



spinning operation. Furthermore, the bearing burned out; so the data for the potentials during rotation are difficult of interpretation. The potentials before the rotor was spun are plotted in Figure 13.

#### Discussion

The most generous evaluation of the results of these experiments that I am able to make is a somewhat negative one. Although the kind of effect which had been originally anticipated was not demonstrated, a technique was developed which promises to yield definite results. Furthermore, some wholly unanticipated phenomena were encountered. Whether these phenomena can be "explained" in terms of more familiar phenomena, or whether they contain new elements can not, as yet, be decided.

The part of the experimental technique which seems to require major attention is the production and maintenance of high and constant vacuum. There should be not only a high pumping speed, but also provision for the prevention of entrance of vapors from the rubber bearing gasket, the lubricating oils, and sealing waxes into the vicinity of the rotor and electrode. (Many trapping devices suggest themselves for this purpose.) The imperfect vacuum conditions seem to have been responsible for lack of constancy in the contact potential differences, and this lack was responsible for failure to attain the precision of measurement which could have revealed effects of the magnitude predicted by the idealization already given. This magnitude is about three microvolts for the velocities possible with this apparatus. (The sensitivity of the amplifier is adequate.)

Unfortunately, only aluminum alloys were tried in these experiments. The choice of materials was limited by the requirement for high tensile strength. There is little doubt but that the surfaces encountered during these experiments were never free of oxides. Perhaps the use of other materials, such as copper alloys, tungsten, or tantalum, whose surfaces may be more easily

prepared in an oxide free condition, would have been preferable. In any event, results with very different materials would be interesting.

Another disturbing factor which must be considered is the effect of external magnetic field. In this apparatus the heavy steel chamber yielded considerable magnetic shielding, for no effect on the potential was discernible when a powerful permanent magnet was brought close to the apparatus while the rotor was spinning. Nevertheless, means were provided for reversal of the direction of rotation. Should it ever be possible to obtain reproducible measurements reversal of direction of rotation would be an important aid in the disentanglement of "intrinsic" effects connected with the rotation from effects which result from interaction with external agencies.

Perhaps the charge gathering phenomena in insulated systems are worthy of mention. Quite consistently the stationary rotor gained negative charge; in the few instances in which the measurements were made the spinning rotor lost negative charge. Whether the latter effect resulted from friction against the gas remaining in the chamber even at  $2 \times 10^{-6}$  mm. or is an intrinsic rotational effect can hardly be decided from the meager data. But the very fact that there may be an intrinsic effect of this kind is so intriguing that further work would seem to be of value.

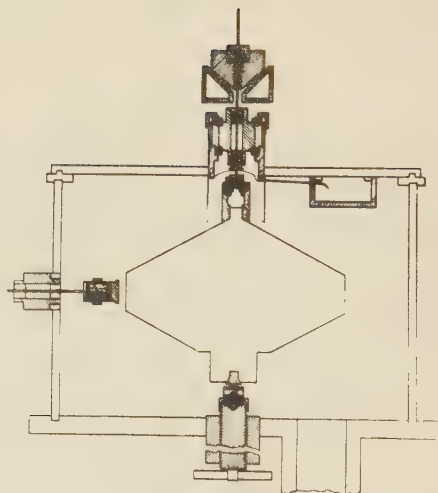


Fig. 2

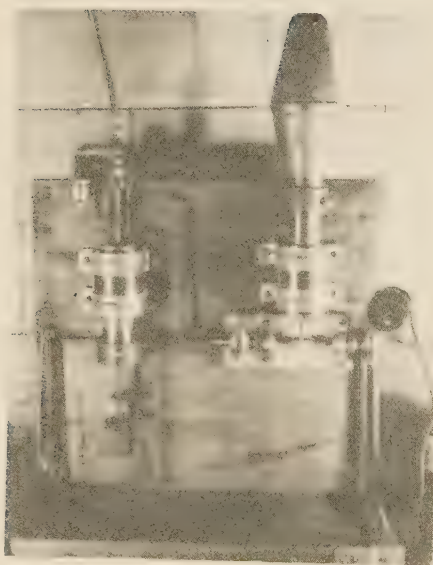


Fig. 3

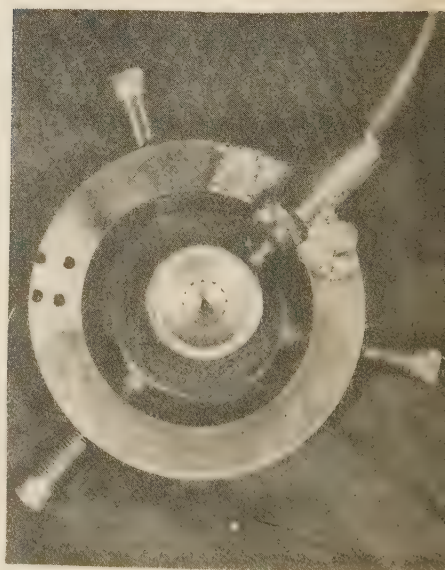
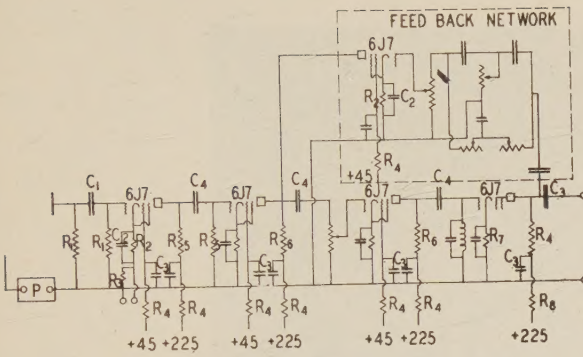


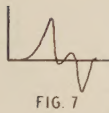
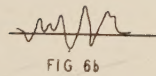
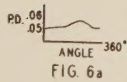
Fig. 4



$R_1 = 10^8$  ohms  
 $R_2 = 3500$  ohms  
 $R_3 = 2.5$  ohms  
 $R_4 = 50000$  ohms  
 $R_5 = 500000$  ohms  
 $R_6 = 250000$  ohms  
 $R_7 = 2500$  ohms  
 $R_8 = 10000$  ohms

$C_1 = .0001$  mf.  
 $C_2 = 25$  mf.  
 $C_3 = 1$  mf.  
 $C_4 = .004$  mf.

Fig. 5



COUNTERCLOCKWISE

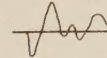
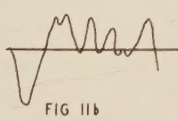
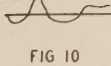
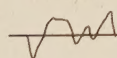


FIG. 8

CLOCKWISE





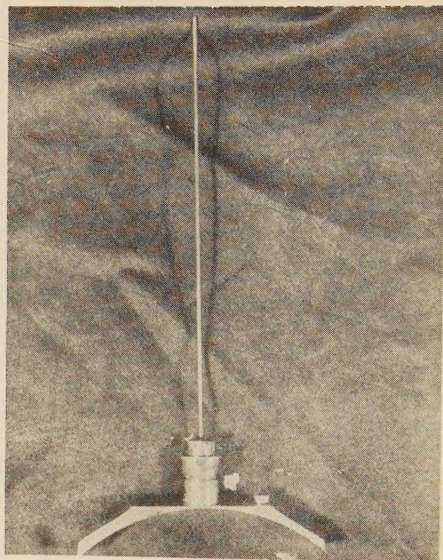


Fig. 9

